REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
29-07-2014

2. REPORT TYPE
Conference Proceeding

3. DATES COVERED *(From - To)*

4. TITLE AND SUBTITLE
Validation of Ocean Color Sensors Using a Profiling Hyperspectral Radiometer

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER
0602435N

6. AUTHOR(S)
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5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER
73-6552-03-5

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Naval Research Laboratory
Oceanography Division
Stennis Space Center, MS 39529-5004

8. PERFORMING ORGANIZATION REPORT NUMBER
NRL/PP/7330--14-2154

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Office of Naval Research
One Liberty Center
875 North Randolph Street, Suite 1425
Arlington, VA 22203-1995

10. SPONSOR/MONITOR'S ACRONYM(S)
ONR

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release, distribution is unlimited.

13. SUPPLEMENTARY NOTES

20140805589

14. ABSTRACT
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15. SUBJECT TERMS
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16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
Unclassified	Unclassified	Unclassified	UU	12	Wesley Goode
					19b. TELEPHONE NUMBER *(Include area code)* (228) 688-5265

Validation of Ocean Color Sensors Using a Profiling Hyperspectral Radiometer

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ABSTRACT

Validation measurements of satellite ocean color sensors require in situ measurements that are accurate, repeatable and traceable enough to distinguish variability between in situ measurements and variability in the signal being observed on orbit. The utility of using a Satlantic Profiler II equipped with HyperOCR radiometers (Hyperpro) for validating ocean color sensors is tested by assessing the stability of the calibration coefficients and by comparing Hyperpro in situ measurements to other instruments and between different Hyperpros in a variety of water types. Calibration and characterization of the NOAA Satlantic Hyperpro instrument is described and concurrent measurements of water-leaving radiances conducted during cruises are presented between this profiling instrument and other profiling, above-water and moored instruments. The moored optical instruments are the US operated Marine Optical BuoY (MOBY) and the French operated Boussole Buoy. In addition, Satlantic processing versions are described in terms of accuracy and consistency. A new multi-cast approach is compared to the most commonly used single cast method. Analysis comparisons are conducted in turbid and blue water conditions. Examples of validation matchups with VIIRS ocean color data are presented. With careful data collection and analysis, the Satlantic Hyperpro profiling radiometer has proven to be a reliable and consistent tool for satellite ocean color validation.

Keywords: Satlantic Hyperpro, In Situ Measurements, Ocean Color Validation, VIIRS

1. INTRODUCTION

Since the Coastal Zone Color Scanner (CZCS) days it was generally accepted that the validation of satellite ocean color sensors is essential. Particularly, water-leaving radiance of which all other products are derived. This validation is independent of sensor vicarious calibration which has traditionally utilized data from MOBY. After the evaluation of the CZCS performance, validation requirements were identified and National Aeronautics and Space Administration (NASA) established the SeaWiFS validation measurement protocols to provide a consistent and accurate time series of ocean color data[1]. These were later updated for the Sensor Intercomparison and Merger for Biological and Interdisciplinary Oceanic Studies (SIMBIOS) Project[2]. The overall product uncertainty goals for water leaving radiances, which are measured by satellite ocean color sensors, are less than 5%. This goal cannot be achieved without accurate vicarious calibration and continuous monitoring of complete system performance via product in situ validation. NOAA NESDIS MOBY Team members have been performing these validations since CZCS[3] in collaboration with NASA, Naval Research Laboratory (NRL) and academia.

While the MOBY data set has proven to be an invaluable tool for ocean color sensor vicarious calibration[4] as well as validation, augmentation to this effort using a variety of different platforms is required to increase the temporal and spatial distribution of validation data. The types of platforms can be buoys (Boussole), stationary platforms (Aeronet), and in-water and above water shipboard measurements. All these techniques have scaling and measurement limitations. The NOAA JPSS Cal/Val Team utilizes all these platforms for VIIRS initialization to maximize coverage and expedite validation. One of the primary in-water instruments used by NOAA for validation measurements is the Satlantic Hyperspectral Profiling Radiometer (Hyperpro). The Hyperpro is a portable, nearly self contained in-water radiometer that provides measurements of up-welled radiance (L_u) down-welled irradiance (E_d) with depth and surface incident

Ocean Sensing and Monitoring VI, edited by Weilin W. Hou, Robert A. Arnone, Proc. of SPIE
Vol. 9111, 91110Y · © 2014 SPIE · CCC code: 0277-786X/14/$18 · doi: 10.1117/12.2052933

irradiance (E_s) to calculate remote sensing reflectance (http://satlantic.com). The stability and ease of use of this instrument allows researchers the ability to sample at a comparatively high temporal and spatial rate and with defined uncertainties[5]. The rapid sample rate of the Hyperpro offers the opportunity to characterize numerous pixels within an image that stationary platforms are incapable of sampling. The NOAA Hyperpro has been used as the primary in situ instrument for the NESDIS Chesapeake Bay Optical Characterization Experiment (COCE) to develop MODIS Aqua regional remote sensing ocean color algorithms[6] and has demonstrated the capacity to provide in situ validation data[7].

This paper will focus on the capability of the NOAA Hyperpro as a contributing in-water in situ data source for satellite ocean color validation. This includes an evaluation of the Hyperpro calibration stability, instrument repeatability, comparison to other validation techniques and data processing protocols. These evaluations will assist in demonstrating that Hyperpro measurements are acceptable for ocean color validation activities.

2. BACKGROUND

Shipboard validation measurements include ship mounted or hand held above- and in-water instruments and now includes radiometers suspended just above the surface[8]. Errors and uncertainties are inherent with each of these techniques. In the past, most validation projects utilized multiband instruments that collected data using bands corresponding to the ocean color sensors being evaluated such as SeaWiFS or MODIS. However, as each instrument has slightly different band characteristics, these validation data had to be adjusted to account for shifts in spectral band centers between ocean color missions (http://oceancolor.gsfc.nasa.gov/DOCS/RSR_tables.html). Hyperspectral measurements had the advantage in that the measurements could be spectrally weighted to any ocean color sensor. Until recently, hyperspectral instruments had to be custom made and were expensive[9]. Today, there are a number of commercial hyperspectral instruments that are being characterized and utilized by numerous ocean color validation team members. One of those instruments that is gaining acceptance in the community is the Satlantic Hyperpro profiling system for measuring normalized water leaving radiance or remote sensing reflectance. This instrument is the hyperspectral successor of the multiband Satlantic radiometers which have up to 7 bands corresponding to ocean color satellite sensors.

The Hyperpro has been used to validate MODIS Aqua (Figure 1) and MERIS[10] in the past. MODIS Aqua is well characterized and validated and matchups in Figure 1 are expected to agree well. MODIS Aqua is currently being used operationally at NOAA to meet NOAA user requirements for many applications including Harmful Algal Bloom Bulletins[11] and other fisheries applications[12]. MODIS Aqua was launched in May 2002 with a life expectancy of 6 years which means it has already doubled its life expectancy. NOAA is currently at risk of not having an operational ocean color sensor. It is imperative that JPSS VIIRS sensor be validated and transitioned operationally as soon as possible. Here we demonstrate a tool that can be utilized to initialize, improve and validate VIIRS so it can be used to satisfy NOAA operational needs. Some of the Hyperpro uncertainties have been described in Voss et. al., 2010 while exploring alternative vicarious calibration techniques. Here, that evaluation is continued and explored in context of a validation tool. In this report, the Hyperpro is inter-calibrated, variability between multiple Hyperpros is accessed, and comparisons are run with above water radiometers and two vicarious calibration buoys.

The Satlantic Hyperpro is a free-falling profiling radiometer used to make hyperspectral profiles of downwelling irradiance and upwelled radiance to calculate water-leaving radiances measured by ocean color satellites. The principle component for the radiance and irradiance measurements on the Hyperpro are the HyperOCR Hyperspectral Radiometers. The HyperOCR utilize a 256 channel silicon photodiode array detector with a full spectral range of 305-1100 nm but is only calibrated from 350-800 nm. They have a spectral resolution of 10 nm sampled at every 3.3 nm. The HyperOCRs are cylindrical in shape and have an effective diameter of only 6 cm to reduce instrument shadowing. The downward looking radiance (L_u) HyperOCR and the upward looking irradiance (E_d) are mounted on the side of a profiler which is designed to minimize shadowing from the profiler and maximize distance from the boat in order to avoid ship shadows. The HyperOCRs are all thermally characterized for temperature corrections and spectrally characterized to account for stray light corrections. The Hyperpro can be powered by a DC power supply or directly from a 12V battery making it versatile and portable. The instrument is typically deployed by hand off the boat and yoyo'ed in the water to allow the instrument to kite away from the platform. The E_s sensor(s) are mounted on deck in a way to avoid any structure shadow. The exercise below is essentially a validation of the ocean color satellite validation instrument using inter-calibrations and inter-comparisons.

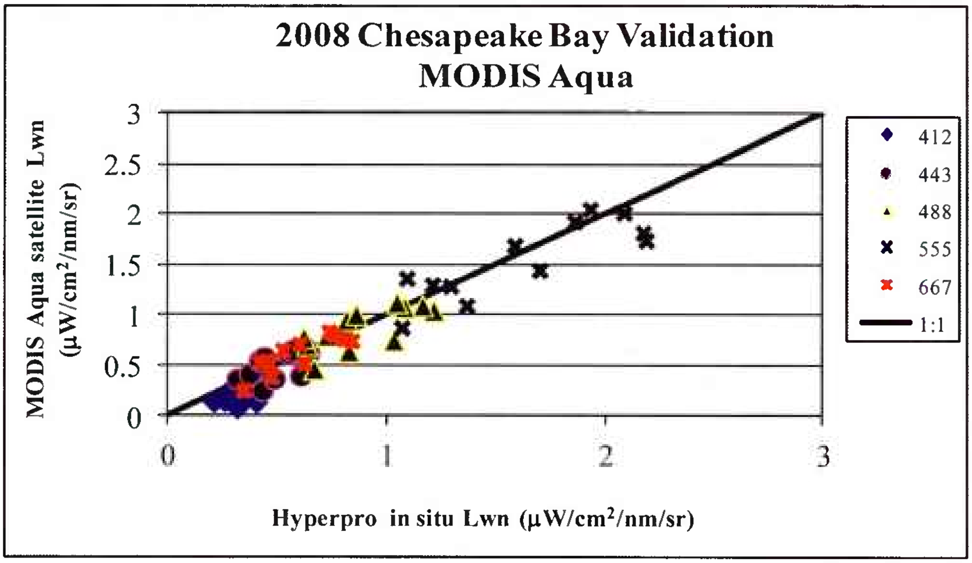


Figure 1. Validation of MODIS Aqua ocean color sensor using in situ Chesapeake Bay Lwn data collected in 2008. The solid line is the 1:1 line. Hyperpro in situ measured Lwn was measured using the NOAA Hyperpro profiler and processed as described in Ondrusek et. al., 2012. The MODIS Aqua data are NASA Ocean Color Biology Group data processed with standard SeaDAS processing.

3. RESULTS

3.1 Calibration stability

Satlantic Hyperpros are designed to be sent back to the manufacturer in Canada for calibration. Cost of the calibration and international shipment to Satlantic generally limits the calibration to once per year depending on frequency of use. If calibrating once per year, a validation measurement made just before the due calibration date, uses a calibration that is nearly a year old. To test the errors associated with annual calibrations and to test if this frequency is adequate for ocean color validation, The NOAA Hyperpro radiance collector response factors from 2009 to 2014 are plotted in Figure 2A for the wavelengths corresponding to the VIIRS bands M1-M6. During this period, no internal maintenance to the instruments was conducted that would physically alter the calibration coefficients. The values, averages and standard deviation are listed in Table 1A. The response factors for the NOAA Hyperpro E_s irradiance collector is plotted in Figure 2B and the values listed in Table 1B while the values for the NOAA Hyperpro E_d irradiance collector is plotted in Figure 2C with values in Table 1C. For the L_u radiance collector calibrations, one standard deviation is generally less than one percent of the average indicating a stable instrument response over time. Variability in the two irradiance collectors is higher and less stable (one standard deviation is 1 to 3 % of the average) potentially introducing extra errors in validation measurements between calibrations.

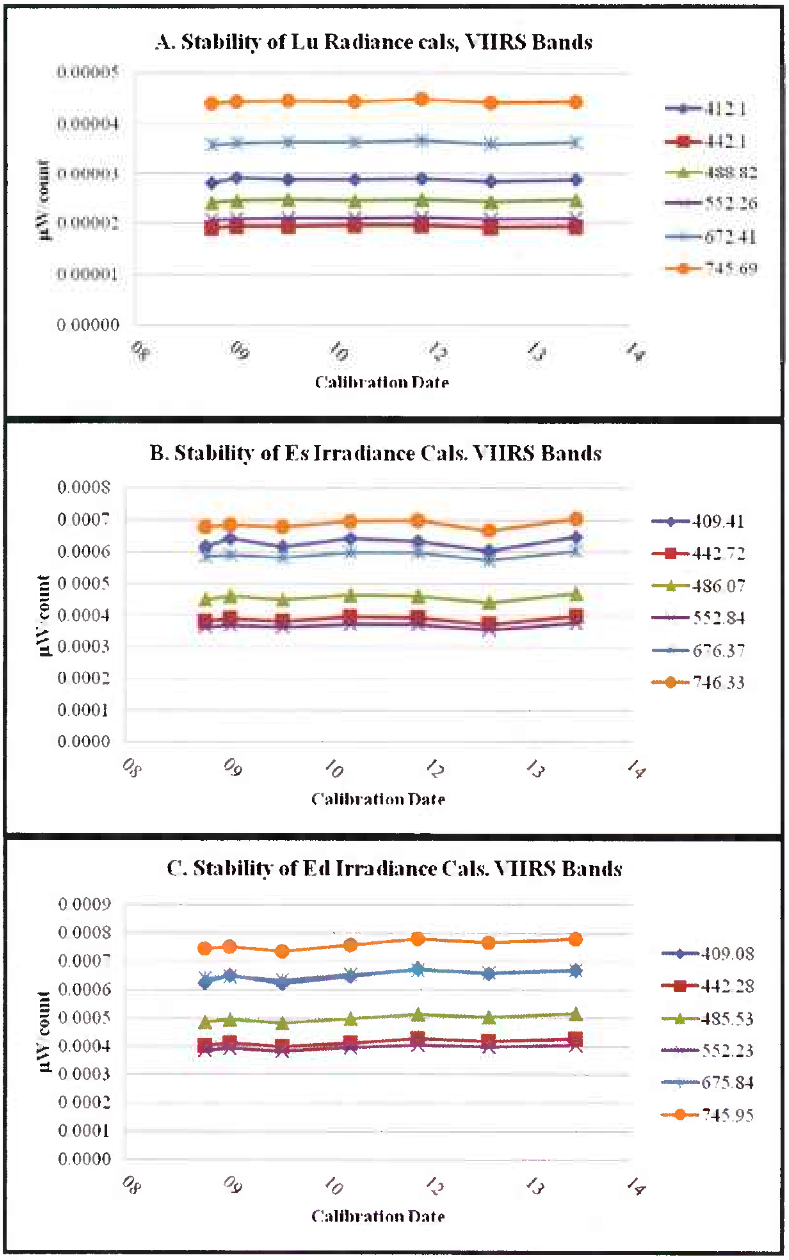


Figure 2. Plot showing response factors in µW/count for annual calibrations of the NOAA profiler, conducted at Satlantic Inc., Nova Scotia, Canada. Bands plotted are closest Hyper OCR band to VIIRS band M1 to M6 peaks. A) NOAA L_u radiance collector, B) NOAA E_s irradiance collector, C) NOAA E_d irradiance collector.

Table 1. Calibration response factors (nW/count) for the three NOAA HyperproOCRs along with average and standard deviation. A) L_u radiance collector, B) E_s irradiance collector, C) E_d irradiance collector.

A. Lu	412.1	442.1	488.82	552.26	672.41	745.69
3/19/2009	0.0281	0.0191	0.0240	0.0207	0.0359	0.0440
7/22/2009	0.0291	0.0195	0.0245	0.0209	0.0363	0.0443
4/7/2010	0.0288	0.0195	0.0246	0.0211	0.0365	0.0445
3/9/2011	0.0289	0.0196	0.0246	0.0210	0.0364	0.0443
2/9/2012	0.0289	0.0196	0.0247	0.0212	0.0368	0.0449
1/24/2013	0.0284	0.0193	0.0242	0.0208	0.0361	0.0441
3/31/2014	0.0288	0.0196	0.0246	0.0210	0.0364	0.0443
Average	0.0287	0.0194	0.0245	0.0210	0.0364	0.0443
Std Dev.	0.0003	0.0002	0.0002	0.0002	0.0003	0.0003

B. Es	409.41	442.72	486.07	552.84	676.37	746.33
3/19/2009	0.616	0.381	0.450	0.364	0.583	0.679
7/22/2009	0.640	0.390	0.459	0.368	0.590	0.685
4/7/2010	0.614	0.380	0.450	0.363	0.581	0.679
3/9/2011	0.639	0.393	0.463	0.372	0.597	0.694
2/9/2012	0.632	0.391	0.461	0.372	0.598	0.699
1/24/2013	0.605	0.373	0.441	0.355	0.571	0.667
3/31/2014	0.647	0.398	0.470	0.377	0.603	0.703
Average	0.628	0.387	0.456	0.367	0.589	0.686
Std Dev.	0.016	0.009	0.010	0.007	0.011	0.013

C. Ed	409.08	442.28	485.53	552.23	675.84	745.95
3/19/2009	0.623	0.400	0.486	0.386	0.640	0.744
7/22/2009	0.649	0.409	0.496	0.390	0.647	0.749
4/7/2010	0.620	0.397	0.483	0.383	0.632	0.735
3/9/2011	0.646	0.412	0.499	0.394	0.653	0.757
2/9/2012	0.672	0.426	0.515	0.405	0.670	0.779
1/24/2013	0.655	0.416	0.504	0.397	0.659	0.766
3/31/2014	0.669	0.426	0.516	0.405	0.670	0.777
Average	0.644	0.410	0.497	0.392	0.648	0.755
Std Dev.	0.018	0.010	0.011	0.008	0.014	0.016

3.2 Satlantic calibration validations

Two validations of the Satlantic calibrations were conducted between the annual calibrations using NIST traceable calibration sources at the MOBY facility in Hawaii. The first was in September, 2012 and the second in February, 2014. For the 2012 validation, the February 2012 Satlantic calibration was determined to still be valid indicating a stable system response through the year. The same was true with the radiance L_u and irradiance E_d validation shown in Figure 3. However, the E_s (234) OCR measurement of the FEL lamp in February 2014 was consistently around 6% lower than

the predicted values indicating a shift in the calibration from the 2013 calibration conducted at Satlantic. This shift was confirmed in the 3/31/2014 calibration where the E_s irradiance response factor averaged 5.9% higher than the 1/24/2013 calibration (Table 1, Fig. 2B).

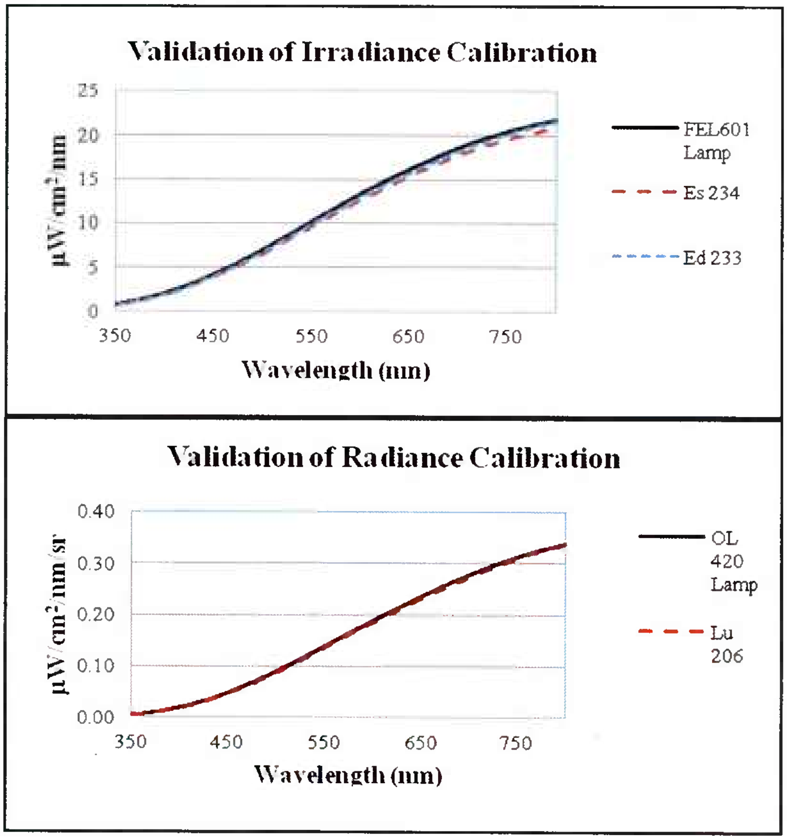


Figure 3. Validation of calibration coefficients conducted in Oahu, Hawaii on February 26, 2014. Top plot shows irradiance validations of the NOAA E_s and E_d OCR sensors using a FEL Lamp. Bottom plot shows the validation of the radiance calibration conducted in Oahu, HI on February 25, 2014 using an OL420 system.

3.3 Variability between different Hyperpro profiling systems.

During a NATO sponsored cruise in August, 2010 in the Mediterranean Sea, simultaneous Hyperpro cast were conducted between three independent Hyperpro profiling systems. The E_s collectors were placed together on deck and the Hyperpros were profiled together to reduce any time differences between measurements. 41 simultaneous Hyperpro stations were occupied in the Ligurian Sea from August 21 to September 1, 2010. For each station, at least one multicast profile and one single cast profile were conducted. Only multicast profiles were included in this analysis. An example spectral comparison for Station 15 collected on August 24, 2010 is shown in Figure 4A along with the mean percent difference between the NOAA Hyperpro (Black/Dash) and the other two identical Hyperpro systems (Red and Green, Figure 4B). The pattern observed in Figure 4A was very consistent throughout all the stations with the green Hyperpro system giving nearly identical results to the NOAA Hyperpro while the Red Hyperpro system measuring on average 2 to 5% higher depending on wavelength. The consistency in the pattern can be observed in the low standard deviations plotted in Figure 4B for wavelengths less than 700 nm. The percent differences are highly variable for wavelengths greater than 700 nm as a result of the low Lwn values which are approaching the Hyperpro sensitivity limits. The constant percent differences indicate that the Hyperpro measurements were consistent and stable and that the Red Hyperpro system had a slightly different calibration.

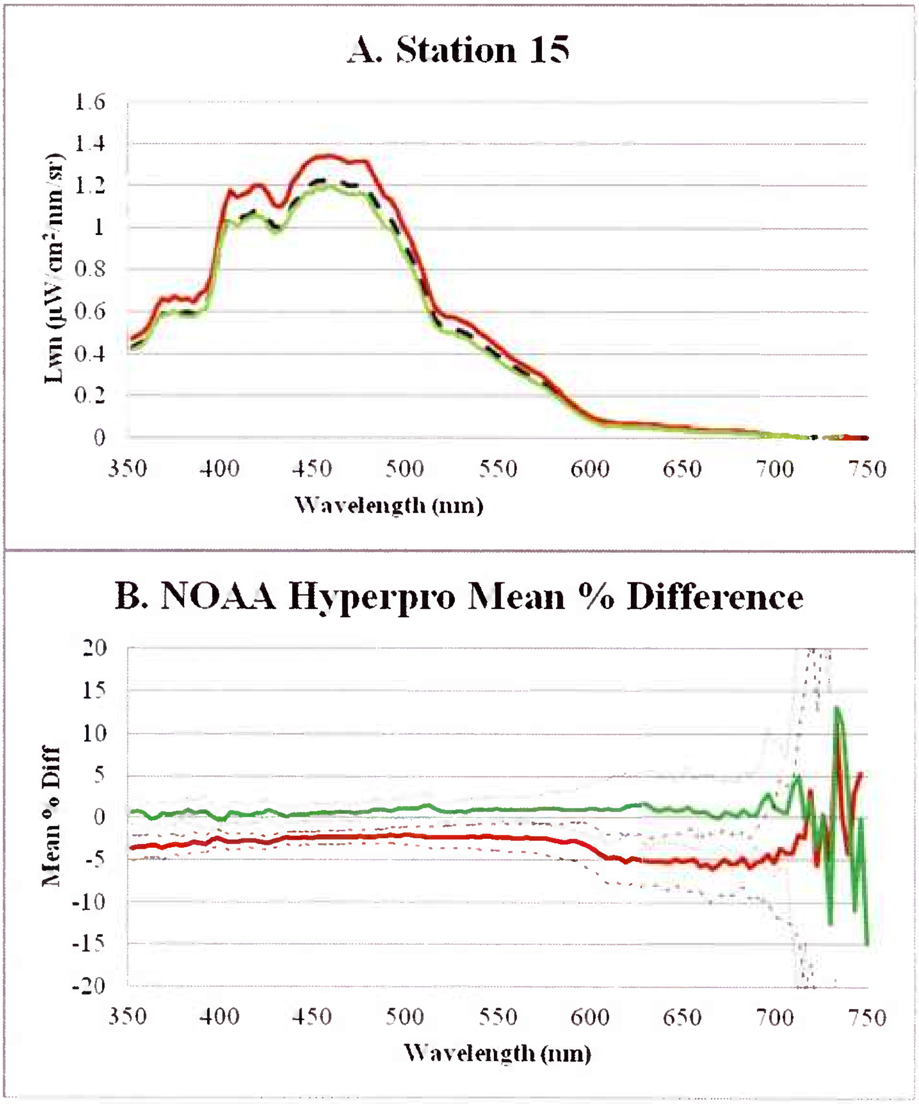


Figure 4. Plot of a representative station from the Mediterranean Sea collected in 2010 (A). B) Mean percent difference (n=24) between the NOAA Hyperpro (Black/Dash, Fig. 4A) and the other two Hyperpro systems. The dotted line for the red (bottom) and dash line for the green (top) are plus and minus one standard deviation.

3.4 Comparison between Hyperpro and vicarious calibration sources.

The NOAA Hyperpro system was compared to the two primary moored vicarious calibration systems used for all international polar orbiting ocean color sensors, MOBY and Boussole. During the Mediterranean cruise, described in section 3.3, Hyperpro measurements were conducted throughout the day on August 30, 2010 in the direct vicinity of the Boussole calibration mooring (http://www.obs-vlfr.fr/Boussole). The NOAA Hyperpro system measured Remote Sensing Reflectance (Rrs) values ranging from 0 to 15% lower than Boussole earlier in the day and 0 to 5% higher in the afternoon (Figure 5). The percent different values were extremely variable at wavelengths above 600nm and are not shown. The NOAA Cal/Val Team conducted coincident Hyperpro measurements with MOBY during an April, 2009 swap out cruise. Again, the values match well with the MOBY values at wavelengths less than 600 nm with percent

differences less than 5% (Figure 6). As with the Boussole comparison, the percent differences increased significantly at the longer wavelengths. MOBY utilizes custom high spectral resolution optics called the Marine Optical System (MOS) which are coupled by fiber-optics to collectors at 3 depths[9]. Boussole, currently and at the time of this study, utilizes HyperOCR radiometers mounted at two depths. The relatively good agreement between the Hyperpro data collected on an arbitrary day and these ocean color standards validates the potential of the Hyperpro as a validation tool.

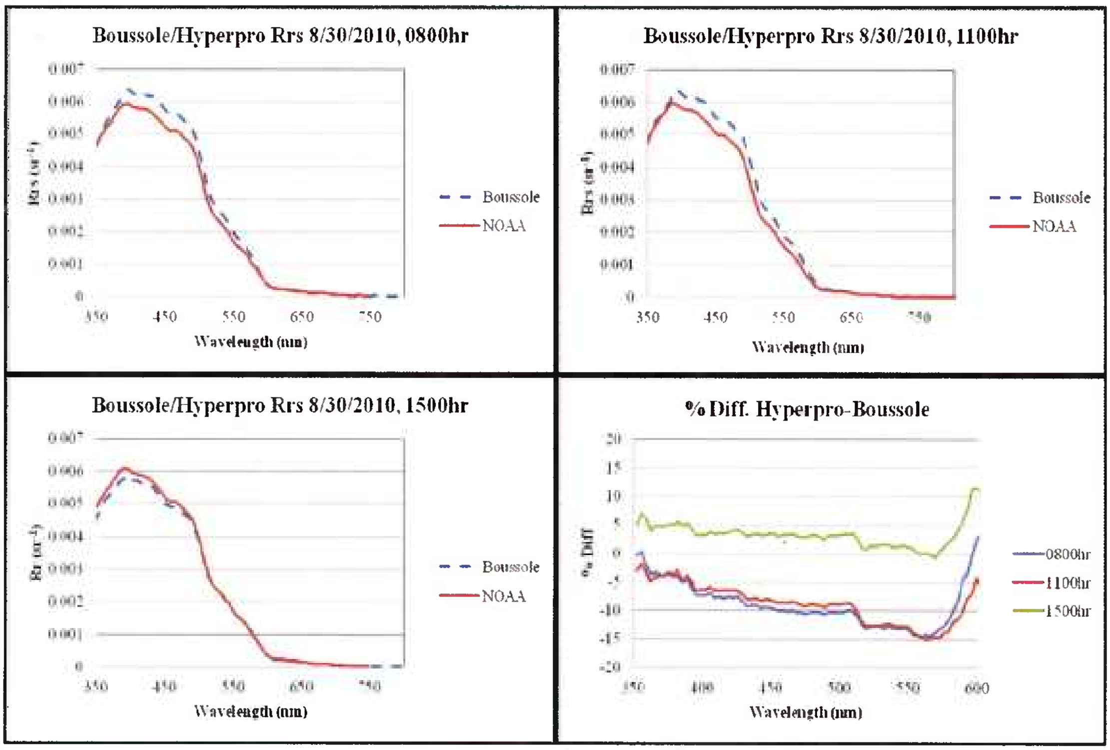


Figure 5. Comparison between NOAA Hyperpro system and Boussolle mooring system. All data were collected on 8/30/2010 within 2 km of the Boussole mooring.

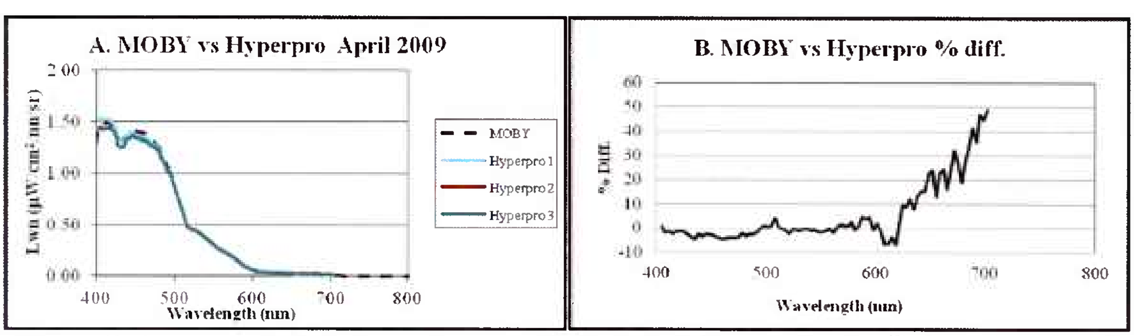


Figure 6. Comparison between NOAA Hyperpro system and MOBY mooring system. Simultaneous Hyperpro data collected 4/17/2009 during MOBY swap out.

3.5 Comparison to above-water Rrs measurements

To evaluate the Hyperpro in-water validation estimates against above-water estimates, comparisons were run with an ASD Inc. HandHeld 2 (http://www.asdi.com) portable spectroradiometer during a cruise off South Florida. The cruise was out of the University of Miami as part of the South Florida Program Cruise Series aboard the R/V Walton Smith

from February 27 to March 02, 2012. Approximately 21 optical stations were occupied throughout the South Florida region and the Florida Keys. Figure 7 is a plot of ASD Hand-Held 2 above water Rrs values plotted against near-simultaneously collected Hyperpro estimates. The Hyperpro measurements were conducted directly after the above-water measurements. Only stations that had clear sky with retrievable satellite data were used in the analysis. The data showed good agreement with an averaged r-squared for all the bands of 0.98.

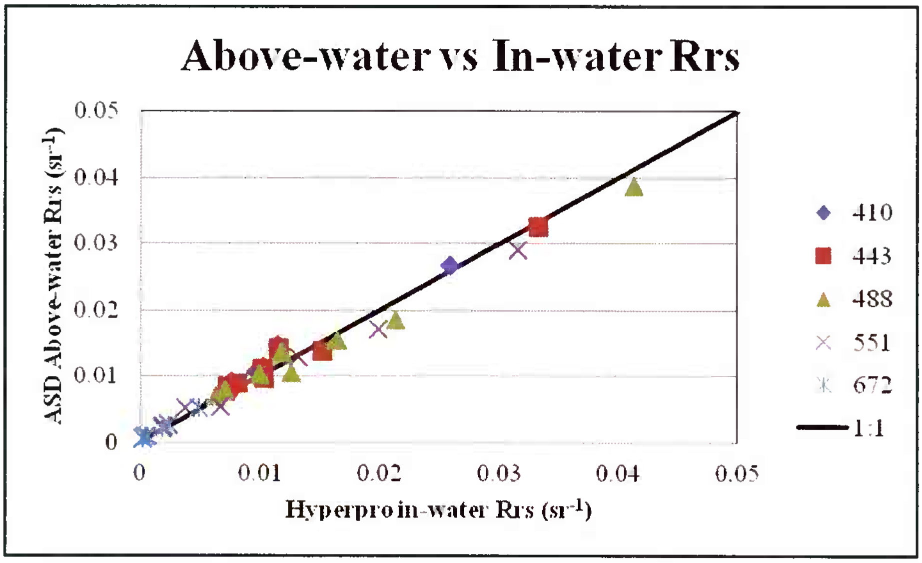


Figure 7. Crossplot of above-water and in-water estimates of Rrs (sr^{-1}) collected during a South Florida Program cruise from February 27 to March 2, 2012. The Hyperpro and ASD hyperspectral data were spectrally weighted to VIIRS bands. The Mean r-squared determined for all bands combined was 0.98.

3.6 Hyperpro processing protocols

Hyperpro data are designed to be processed with Satlantic Prosoft Software. The current processing version released for Prosoft is version 7.7.16. This processing software utilizes an older method that uses single cast collection and processing techniques that can introduce several errors and inconsistencies when calculating water-leaving radiance. Zibordi et. al., (2004) identified minimum requirements for measurement depth resolution when conducting in-water optical validation measurements. The minimum depth resolution calculating L_u just below the surface $L_u(0-)$ was 11 cm. and for K_d (diffuse attenuation coefficient) was identified at 2 cm. Even with the Hyperpro weights adjusted perfectly for water column density, the minimum descent rate achievable is 0.1 – 0.2 m/sec, the required depth sampling resolutions described in Zibordi et. al., 2004 were near impossible to achieve. Another problem with the version 7 Prosoft software is that the data are depth and time binned in calculating K_d which is used to calculate Lwn. Using different binning parameters yields different Lwn values for the same profile. This will ultimately lead to inconsistencies in validation data sets collected and processed by different investigators. In 2008, Satlantic introduced an 8.0 Prosoft version which included a multi-cast technique in collecting and processing the data. Using this multi-cast technique, the Hyperpro is YOYO'ed (allowed to sink freely then pulled back up to surface) up and down near the surface (10 m for case II waters and 20 m for case I waters) while collecting all the data into a single raw file. All the data are then used in the processing of K_d and the Level 3 binning used in previous versions is omitted. This technique allows the utilization of hundred's of readings per meter in the upper water column thus satisfying the requirements outlined in Zibordi et. al., (2004) and eliminates inconsistencies between investigators due to binning parameterizations during processing. Other improvements introduced in version 8.0 include:

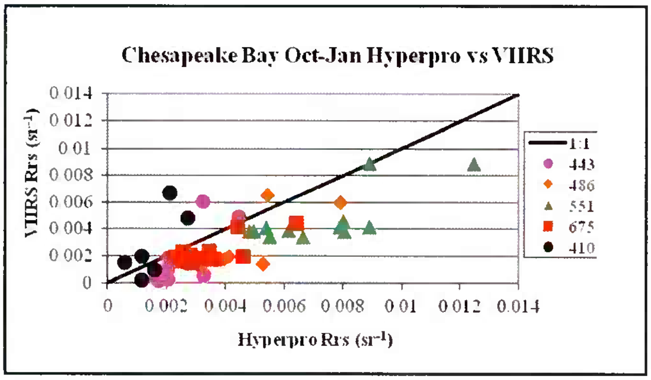
- Stray light correction
- Thermal responsivity correction
- Introduction of Thuillier extraterrestrial irradiance

- Processing of Ecopuc data in multicast level 4 files
- Normalization of profiles for Es collected during the profile.

The latest versions of Prosoft are being tested by the JPSS Cal/Val Team and readied for release.

4.0 VIIRS VALIDATION APPLICATION

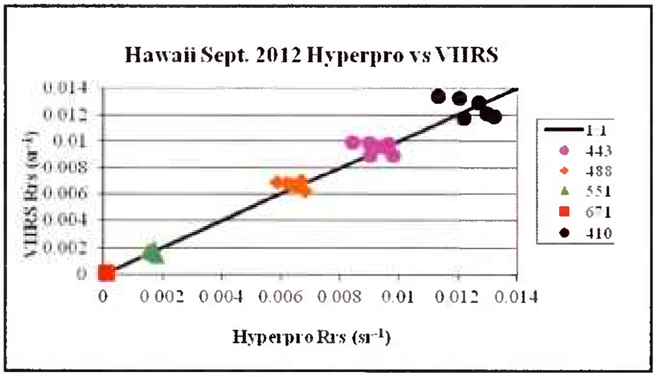
The NOAA/NESDIS/STAR JPSS Cal/Val Team has collected hundreds of validation stations since the launch of Suomi VIIRS. The sampling regions include the Chesapeake Bay, South Florida, Hawaii, and the Gulf of Mexico. Typical data collected for each station include Hyperpro in-water measurements, ASD above-water measurements, Wetlabs Ecopuc backscatter data, aerosol optical thickness using a Solar Light, Inc. MicroTops sun photometer, CTD, and fluorometric and extracted chlorophylls. All validation data are analyzed and distributed to agencies responsible for VIIRS evaluations. This includes the JPSS Cal/Val Team, NOAA, NRL, NASA and academia. No attempt is made here to evaluate the performance of the JPSS VIIRS sensor as processing versions and look up tables are constantly evolving requiring constant new validation measurements. At the present time, JPSS is not reprocessing past VIIRS data and therefore validations only apply to the data processed at the time of collection. Examples of VIIRS validation during the initialization period are given below; however, it should be kept in mind that the VIIRS performance at all bands have changed since these periods. Figure 8 gives an example of validation measurements and VIIRS performance collected in the Chesapeake Bay for a period of October 2012 to January 2013. The NOAA NESDIS Cal/Val Team conducts routine validation in the Mid- to Northern sections of the Chesapeake Bay in collaboration with the NOAA Chesapeake Bay Office, Annapolis, MD. Over 120 validation stations have been collected in this region since the launch of VIIRS.



Band (nm)	Avg. % diff. Hyperpro - VIIRS	Std. Dev. of % diff. Hyperpro - VIIRS
410	65.98	113.88
443	-49.99	53.63
488	-46.35	24.05
551	-35.10	15.69
671	-33.47	16.35
Average 443 to 671 nm	-41.23	27.43

Figure 8. VIIRS validation using in situ Hyperpro measurements in the Chesapeake Bay. Data collected in upper Chesapeake Bay from October, 2012 to January, 2013 (n = 12). VIIRS data processed using NASA processing.

In addition to routine validation measurements conducted in the Chesapeake Bay, the NOAA JPSS Cal/Val Team conducts validation measurements on dedicated and cruises of opportunity. We have conducted two cruises in Hawaii since the launch of VIIRS. The example in Figure 9 was collected during an instrument self shading experiment in September, 2012. A Cal/Val experiment was also run in March, 2014 at the MOBY Site (data not shown). The VIIRS performances in Figure 9 are stated as percent difference to the in situ (Hyperpro) data for two different types of processing, NASA and NRL. As expected, the percent differences between VIIRS Rrs and in situ data are much lower for NASA processed data off Hawaii (Figure 9) than the NASA processed data in the Chesapeake Bay (Figure 8). In situ water-leaving radiance measurements are more of a challenge in turbid waters due to shallow attenuation depths and the high horizontal variability found in coastal regimes. As stated before, these are just a few examples of validation measurements conducted during the VIIRS initialization period.



Band	Hyperpro - NASA	Hyperpro - NRL
410	1.50	3.48
443	3.18	1.05
488	3.93	3.38
551	1.40	36.27
671	-8.81	158.79
Average 410 to 551	2.50	11.05

Figure 9. VIIRS validation using in situ Hyperpro measurements off Oahu, Hawaii collected in September, 2012 (n = 6). VIIRS data in the cross plot was processed using NASA SeaDAS. The NASA (SeaDAS) and NRL (APS) processing versions used to generate the table used the experimental, current processing version available in October 2012. Both of these processing codes have been updated several times.

5. CONCLUSION

With good calibration techniques and careful attention to protocols, Hyperpros can provide accurate traceable validation measurements for ocean color data. It is demonstrated that Hyperpro calibrations can be stable for years, however, the calibration has to be monitored constantly to avoid anomalies like that observed in the E_s calibration responses in 2013 (Figs. 2 and 3, Table 1). It is recommended that the HyperOCRs are calibrated at least once a year but more frequent calibrations would greatly increase confidence levels. Repeatability and consistency between Hyperpros are very good (Figure 4). The percent differences between the different Hyperpros are nearly constant as indicated by the standard deviation of the averages in Figure 4. It is recommended when utilizing multiple validation instruments during validation experiments, that the instruments are inter-calibrated. Without an inter-calibration, the differences between the red and green Hyperpros cannot be explained even though these were most likely caused by differences in calibrations.

Comparisons to the two vicarious calibration sources matched well when the systems are both well calibrated. Larger percent differences are observed at wavelengths greater than 600 nm due to the low magnitude of radiance values in this range and poor sensitivity at these values. Comparisons to above-water radiometers worked well off the coast of Florida, however, more analysis needs to be performed in turbid waters where in-water measurement techniques are more difficult.

As mentioned, in situ validations need to be continued throughout the lifetime of any ocean color sensor to monitor end to end system performance. While MOBY and Boussole marine buoys monitor performance in blue water conditions, regional validation measurements need to be maintained in all water types. The Hyperpro offers a convenient, easy to use, stable commercial validation instrument that can be operated on small boats or large ships.

6. ACKNOWLEDGEMENTS

This work is supported by the JPSS EDR Cal/Val program and NOAA Ocean Remote Sensing funding. We would like to acknowledge the help of MOBY Team members. Especially Stephanie Flora from Moss Landing Marine Labs and Carol Johnson from NIST for calibration support. We would also like to acknowledge ZhongPing Lee for cruise support during Hawaii 2012 calibration efforts. The views, opinions, and findings contained in this paper are those of the authors and should not be construed as an official NOAA or US Government position, policy, or decision.

7. REFERENCES

[1] Mueller, J.L. and Austin, R.W., "Ocean Optics Protocols for SeaWiFS Validation," NASA Tech. Memo. 104566, Vol. 5, S.B. Hooker and E.R. Firestone, Eds., NASA Goddard Space flight center, Greenbelt, Maryland, 45 (1992).

[2] Mueller, J.L. ,. Austin, R.W, Morel, A., Fargion, G.S., and McClain, C.R., "Ocean Optics Protocols For Satellite Ocean Color Sensor Validation," NASA/TM-2003-21621/Rev-Vol I, Mueller, J.L., G.S. Fargion and C.R. McClain, Eds. NASA Goddard Space flight center, Greenbelt, Maryland, 50, (2003).

[3] Clark, D. K., "Phytoplankton pigment algorithms for the Nimbus-7 CZCS," [Oceanography from Space], J.F.R. Gower Ed., Plenum Press, 227-238, (1981).

[4] Franz, B.A., Bailey, S.W., Werdell, P. J., and McClain, C.R., "Sensor-independent approach to the vicarious calibration of satellite ocean color radiometry," Applied Optics, 46(22), 5068-5082, (2007).

[5] Voss, K.J., McLean, S., Lewis, M., Johnson, C., Flora, S., Feinholz, M., Yarbrough, M., Trees, C., Twardowski, M., and Clark, D., "An Example Crossover Experiment for Testing New Vicarious Calibration Techniques for Satellite Ocean Color Radiometry," Journal of Atmospheric and Oceanic Technology, 27 1747-1759, (2010).

[6] Ondrusek, M.E., Stengel, E., Kinkade, C., Vogel, R.L., Keegstra, P., Hunter, C., and Kim, C., "The development of a new total suspended matter product for the Chesapeake Bay," Remote Sensing of the Environment, 19, 243-254, (2012).

[7] Arnone R., Fargion G. S., Lawson, A., Martinolich, P., Ladner, S., Davis, C., Trees, C., Lawson, A., Zibordi, G., Lee, Z., Ondrusek, M. and Ahmed, S. "Validation of Ocean Color on VIIRS." Proc. SPIE 8372, (2012).

[8] Lee, Z.P., Pahlevan, N., Ahn, Y., Greb, S., O'Donnell, D. "A robust approach to directly measure water-leaving radiance in the field," Applied Optics, 52(8), 1693-1701, (2013).

[9] Clark, D., Yarbrough, M.A., Feinholz, M., Flora, S., Broenkow, W., Kim, Y.S., Johnson, B.C., Brown, S., Yuen, M., and. Mueller, J.L, "MOBY: A Radiometric Buoy for Performance Monitoring and Vicarious Calibration of Satellite Ocean Color Sensors: Measurements and Data Analyses Protocols, Ocean Optics Protocols for Satellite Ocean Color Sensor Validation," NASA Tech. Memo. 2003-210004/Rev 4./Vol. VI, 3-34 (2003).

[10] Cristina, S.V., Goela, P., Icely, J. D., Newton, A.and Fragoso, B., "Assessment of Water-Leaving Reflectances of Oceanic and Coastal Waters Using MERIS Satellite Products off the Southwest Coast of Portugal," Journal of Coastal Research, 56, 1479-1483, (2009).

[11] Kavanaugh, K., Derner, K., Fishe,r K.M., Davis, E., Urizar, C., and Merlini, R., "Assessment of the Eastern Gulf of Mexico Harmful Algal Bloom Operational Forecast System (GOMX HAB-OFS)," NOAA Technical Report NOS CO-OPS 066, (2013).

[12] Belkin, I.M. and. O'Reilly, J.E, "An algorithm for oceanic front detection in chlorophyll and SST satellite imagery," Journal of Marine Systems. 78, 319-326, (2009).

[13] Zibordi, G., Alimonte, D., and Berthon, J. "An Evaluation of Depth Resolution Requirements for Optical Profiling in Coastal Waters." Journal of Atmospheric and Oceanic Technology, 21, 1059-1073, (2004).